REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
03-01-2018	Final Report	1-Sep-2010 - 31-Aug-2016

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Design of Highly Articulated Mechanism for Surgical Applications	W911NF-10-1-0343
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
	611102

6. AUTHORS	5d. PROJECT NUMBER
Howie Choset	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Carnegie Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213 -3589	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	58061-EG.11

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

Snake robots are highly articulated mechanisms that can thread through tightly packed volumes and access locations that people and machinery otherwise cannot access. These devices come in many forms, including locomoting snakes whose internal undulations allow them to maneuver in difficult to negotiate terrains, as well as fixed-base elephant trunks or probes that can reach into cluttered spaces with minimal invasion. The proposed work focuses on the latter of these devices as they have many applications important to the Army including surgery in the field and surgical bomb disarming.

15. SUBJECT TERMS

Surgical Robots and then Striking Robot Study

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Howard Choset
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					412-268-2495

Agency Code:

Proposal Number: 58061EG   **Agreement Number: W911NF-10-1-0343**

INVESTIGATOR(S):

     Name: Howard Choset
     Email: choset@cs.cmu.edu
     Phone Number: 4122682495
     Principal: Y

     Name: Sylvain Cardin
     Email: sylvain.cardin@tatrc.org
     Phone Number: 3016196968
     Principal: N

Organization: **Carnegie Mellon University**
Address: 5000 Forbes Avenue, Pittsburgh, PA 152133589
Country: USA
DUNS Number: 052184116   EIN: 250969449
Report Date: 31-Aug-2016   Date Received: 03-Jan-2018
Final Report for Period Beginning 01-Sep-2010 and Ending 31-Aug-2016
Title: Design of Highly Articulated Mechanism for Surgical Applications
Begin Performance Period: 01-Sep-2010   **End Performance Period:** 31-Aug-2016
Report Term: 0-Other
Submitted By: Howard Choset   Email: choset@cs.cmu.edu
                                          Phone: (412) 268-2495
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: Motivated by applications in highly confined spaces, this work seeks to advance the state of the art in snake robot technology. Recall that snake robots are highly articulated mechanisms that can thread through tightly packed volumes and access locations that people and machinery otherwise cannot access. These devices come in many forms, including locomoting snakes, as well as fixed-base elephant trunks or probes that can reach into cluttered spaces with minimal invasion. The proposed work focuses on the latter of these devices as they have many applications important to the Army including surgery in the field and surgical bomb disarming. We use minimally invasive surgery as a focal point because minimally invasive surgery has the potential to reduce patient discomfort while expediting recovery and return to normal life. Beyond these benefits, we seek to advance minimally invasive surgery for injured soldiers in the field, so they do not necessarily have to be evacuated to receive care, and can return to their jobs as quickly as possible. This project was extended by a year to consider dynamic motions of snake robots based on our previous geometric mechanics work.

Accomplishments: 1. Installed a snake robot on a conventional robot arm and an AGV to explore issues in cooperative control of an AGV and snake robot
2. Advanced our filtering estimation theory to handle highly non-linear spaces using Lie algebra tools
3. Investigated novel means by which we can infer or sense force at the tip of the snake robot. We have since continued that work beyond this project and developed novel force sensors and palpation algorithms to search for tumors.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: The PI founded a company called Medrobotics and still collaborates with the company. Their interests have focused on base of tongue and throat operations with a snake robot. Two years ago, the surgical snake robot advanced by Medrobotics was cleared by the FDA. The PI had a marginal contribution to that process. The PI's medical robot is actually the first medical robot to clear the FDA with the word "robot" in its indication.

PARTICIPANTS:

Participant Type: Faculty
Participant: Howie Choset
Person Months Worked: **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Matt Travers
Person Months Worked: 2.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Stephen Tully
Person Months Worked: 6.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Sidd Sanan
Person Months Worked: 12.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Staff Scientist (doctoral level)
Participant: Ben Brown
Person Months Worked: 1.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article   Peer Reviewed: N   **Publication Status:** 1-Published
Journal: The Laryngoscope
Publication Identifier Type: Publication Identifier:
Volume: 0   Issue: 0   First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Demonstration of Transoral Surgery in Cadaveric Specimens with a Highly Flexible Robot,
Authors:
Keywords: Snake Robot, Medical robotivs

Abstract: Objectives/Hypothesis: Using human cadavers, we investigated the feasibility of using a new robotic platform, the Medrobotics Flex System, for laryngeal access and flexible tool delivery to facilitate the performance of pharyngolaryngeal procedures without laryngeal suspension. Our initial trials specifically assess the utility of this experimental robotic system for epiglottectomy and base of tongue resection. Study Design: Feasibility; Level of evidence: NA. Methods: Using standard mouth retractors, the FlexTMrobot was driven via the physician controller to the supraglottic region. Non-crossing, flexible endoscopic tools were inserted through the robot's external tool channels to retract, cauterize, and remove tissue in each procedure type. Mock surgical procedures were performed on the laryngopharyngeal complex including epiglottectomy, base of tongue resection, and vocal cord excision. Time-to-tissue exposure was noted for each procedure. Each epiglottectomy was timed to determine

Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Carnegie Mellon University
Date Received: 08-May-2017   Completion Date: 4/25/12   4:12AM
Title: BodySLAM: Localization and Mapping for Surgical Guidance
Authors: Stephen Tully
Acknowledged Federal Support: **Y**

Design of Highly Articulated Mechanisms for Surgical Applications
Final Report

Proposal Number 58061-EG

Howie Choset
Robotics Institute
Pittsburgh, PA 15215

Program Objective

Motivated by applications in highly confined spaces, this work seeks to advance the state of the art in snake robot technology. Recall that snake robots are highly articulated mechanisms that can thread through tightly packed volumes and access locations that people and machinery otherwise cannot access. These devices come in many forms, including locomoting snakes, as well as fixed-base elephant trunks or probes that can reach into cluttered spaces with minimal invasion. The proposed work focuses on the latter of these devices as they have many applications important to the Army including surgery in the field and surgical bomb disarming. We use minimally invasive surgery as a focal point because minimally invasive surgery has the potential to reduce patient discomfort while expediting recovery and return to normal life. Beyond these benefits, we seek to advance minimally invasive surgery for injured soldiers in the field, so they do not necessarily have to be evacuated to receive care, and can return to their jobs as quickly as possible. This project was extended by a year to consider dynamic motions of snake robots based on our previous geometric mechanics work.

Summary Accomplishments for this project

1. Installed a snake robot on a conventional robot arm and an AGV to explore issues in cooperative control of an AGV and snake robot
2. Advanced our filtering estimation theory to handle highly non-linear spaces using Lie algebra tools
3. Investigated novel means by which we can infer or sense force at the tip of the snake robot. We have since continued that work beyond this project and developed novel force sensors and palpation algorithms to search for tumors.

Accomplishments

We installed our locomoting snake robot onto a mobile base and a conventional arm. The idea is that the reach of the snake robot is quite limited and instead developing a longer snake robot, we placed a snake robot on a conventional robot. The rational is that the conventional robot provides a stable base and large displacements, whereas the snake robot provides the fine tuned motion. We developed a mechanism to engage the robot both on the AGV and industrial arm. We also

demonstrated the hybrid arm-snake system performing inspections inside of wing bays.
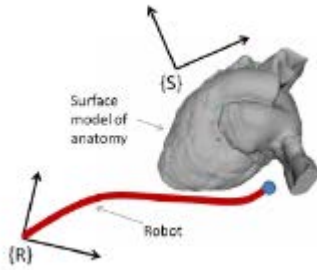
The surgical snake robot is an underactuated system and normally such systems are difficult to control. The surgical snake robot, upon which this work is based, actually has a rather straight forward position control system. The underactuated nature of the robot offers different challenges in estimating the shape of the snake robot, and hence our efforts have been focused in this area. Estimation, using Kalman filter techniques, largely apply to linear systems and like most robots, the surgical snake robot is non-linear. We were, however, able to re-write the Kalman filter estimator in the Lie algebra of the position space of the snake robot, thereby increasing the domain about which linearization provides adequate estimates of the snake robot shape.
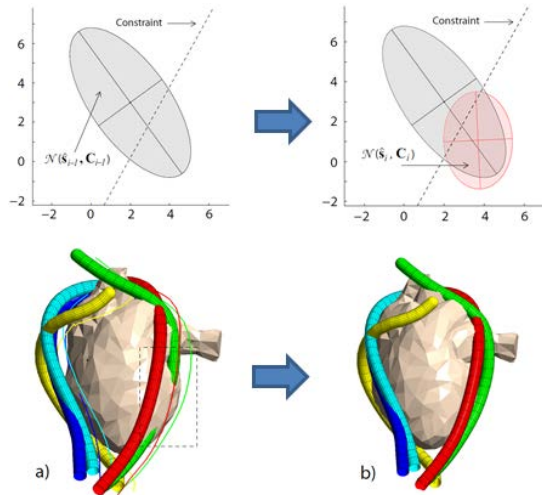
We further advanced our Kalman filtering approach to also properly handle constraints in the environment, which is of particularly great use inside of constrained spaces, such as ordnance, airplane structures, and the anatomy. In this approach, we constantly update the constraint and the state of the system. If the mean state of the system violates the constrain, then the mass of the distribution which violates the constraint is projected onto the constraint. At this point, the distribution is re-normalized back into a Gaussian. While we have not proven this, we have observed in all of our examples that the mean of the distribution never violates the constraint. With this in mind, we can then do a significantly better job estimating the state of the robot in tightly packed spaces.

In this program, we did not accomplish the goal of inferring force information as we had hoped. Since this program ended, we did, however, develop a new force sensor that fits in a compact package and is of low-cost. We are looking to use this sensor in a palpation project.
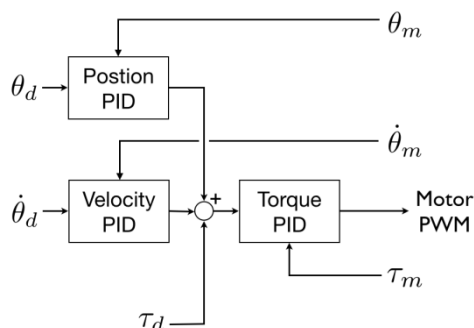
Finally, this project changed directions in its last year to lay down a foundation on how snake robots can use force information to maneuver through tight spaces, with the idea of us developing a future program in snake striking with Dan Goldman at GA Tech. We used an existing snake robot in the Biorobotics Lab at Carnegie Mellon to develop force-based controllers for the robot. The snake robot used is

composed of series elastic actuators; these actuators have a torsional spring in series with their motor output. Encoders on both sides of the spring measure the torsional deflection and therefore the force imparted onto and from the environment. With this robot, we were able to create a controller that combines position, velocity and force. With this in mind, we developed a new compliant controller that closes the loop on the parameters of the shape space, which we used in our previous work in geometric mechanics to design gaits in the first place. Interestingly, we were able to test our approach in a peg-board, suggested by Goldman's group, and were able to replicate different types of animal behavior depending upon "how kinematic" or "how dynamic" our controllers desired and the animals demonstrated

We also dedicated time in the final year to lay out a program in impulsive motion planning for striking plants and animals. We were able to generate a taxonomy of striking mechanism that applied to both biological and mechanical systems. Our hope is to continue this work, if funding should come available.

Relevance to Army

The significance of the proposed work is straightforward: the deployed military stands to benefit from the unique potential benefits of snake robots, whether it is in the medical domain or the inspection of high-value targets. In medicine, single port access offers minimal somatic pain, minimal or absent wound and scarring, quicker recovery from surgical procedures, as well as the dramatic reduction of resources from a sterile environment (operating room). Beyond single port access, natural orifice translumunal endoscopic surgery offers another profound impact for both military and civilian medical care: many of the procedures would not have to be performed in a sterile field. This brings surgical care outside of the hospital. Therefore, procedures otherwise relegated to sterilized surgery can happen away from centers of medical excellence, allowing soldiers to receive minimally-invasive surgical care in forward surgical teams and combat support hospitals. Thus, a soldier can receive care, such as a cholecystectomy, not only physically recovering in a matter of hours, but doing so without leaving the battlefield.

Collaborations and Technology Transfer

The PI founded a company called Medrobotics and still collaborates with the company. Their interests have focused on base of tongue and throat operations with a snake robot. Two years ago, the surgical snake robot advanced by Medrobotics was cleared by the FDA. The PI had a marginal contribution to that process. The PI's medical robot is actually the first medical robot to clear the FDA with the word "robot" in its indication.

Resulting Journal Publications
A Filtering Approach for Image-Guided Surgery with a Highly Articulated Surgical Snake Robot, S. Tully and H. Choset, Transactions on Biomedical Engineering

Simultaneous Compliance and Registration Estimation for Robotic Surgery
Siddharth Sanan , Stephen Tully , Andrea Bajo , Nabil Simaan and Howie Choset
Proceedings of Robotics: Science and Systems, Berkeley, USA, 2014

Monocular Feature-Based Periodic Motion Estimation for Surgical Guidance
S. Tully, G. Kantor and H. Choset. Proceedings of the IEEE International Conference on Robotics and Automation, Karlsruhe, DE, May, 2013.

Constrained Filtering with Contact Detection Data for the Localization and Registration of Continuum Robots in Flexible Environments. S. Tully, A. Bajo, G. Kantor, H. Choset and N. Simaan. Proc. 2012 IEEE International Conference on Robotics and Automation, St. Paul, MN, May, 2012.

Personnel Involved During Reporting Period
- Stephen Tully, PhD, who did a bulk of the filtering and control work supported by this effort and then upon graduation, took a job at Medrobotics.
- Sidd Sanan, PhD is my post-doc who continued Dr. Tully's work for about a year
- Matt Travers is my post-doc and was partially supported by this grant as the change of direction in the completed work on impulsive motions
- Ben Brown is a project scientist and was partially supported by this grant to develop to develop simple mechanisms to demonstrate impulsive motions